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A Review of Circular Economy Research for Electric Motors and the Role of Industry 4.0 Technologies

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Abstract: The market for electric motors is experiencing a step-growth due to their adoption across a range of industrial sectors. This increased demand also highlights the importance of end-of-life management of electric motors and a requirement for appropriate strategies for the high value materials embedded in them. This paper aims to offer a holistic view on the circular economy research for electric motors and the role of Industry 4.0 technologies by presenting the state-of-the-art available in literature and comparing it with the industrial perspective. The literature review revealed the absence of a methodology for selecting the best end-of-life scenario for industrial electric motors. Recycling, which is an end-of-product-life strategy, was found to be the key focus area of research. Reuse, which is a better strategy in terms of waste hierarchy, was the least researched area due to lack of information about the condition and availability of returned products. In order to capture the current landscape within the UK for the repair, remanufacture and recycling of electrical machines, a structured survey of UK based companies was conducted. The survey revealed that nearly half of the companies do not undertake any repair strategies for electrical machine components; however, there was an aspiration from the respondents to migrate their companies towards more sustainable activities. The industry survey and the review of existing literature led to the identification of research trends, challenges and recommendations for future research.

Keywords: electrical machines; circular economy; remanufacturing; Industry 4.0

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1. Introduction

Electric motors have recently received a great deal of attention due to an inexorable growth in their adoption across numerous industrial sectors such as automotive, aerospace, industrial machinery and consumer appliances. Motors consume approximately 40% of the world's electricity and contribute to around 13% of global carbon emissions [1]. The electric motor market is expected to grow to USD 169 billion by 2026, at an annual growth rate of 6.9% from an estimated USD 113 billion in 2020 [2]. The increase in market size for electric motors presents challenges for end-of-life management of electric motors and a requirement for appropriate strategies for high value materials. A report by the European Commission published in 2020 [3] predicted that by the end of 2050, the European Union would require 15 times more cobalt and 10 times more rare earth materials as compared to current consumption. However, the worldwide recycling rate for high value, rare earth materials used in electric motors is less than 3% [3], even though these materials contribute to around 40–60% of the costs in a permanent magnet motor [4]. In the UK alone, the market for the repair and maintenance of electric motors and generators was over USD 580 million, and above USD 5 billion within the EU in the year 2015 [5]. Many countries are targeting the delivery of a Net Zero future, and in order for the UK to meet its target of 80% reduction in carbon emissions by 2050, there is an immediate necessity to accelerate the move to a more sustainable, resource-efficient circular economy (CE).

The Ellen MacArthur Foundation has defined the CE as 'an industrial economy that is restorative by intention and design' [6]. The CE aims to keep resources in use for as long as possible, extracting the maximum value from them while they are in use and then recovering and regenerating products at the end of each service life [7]. Within a manufacturing environment, three CE strategies have been identified for enhancing resource productivity: (i) increasing the utilisation of the resource (enhanced resource productivity), (ii) growing the lifespan of resources (durable design, reuse, remanufacture), and (iii) cascading the resource through added use cycles (component harvesting, recycle) [8,9]. However, in manufacturing companies, the CE implementation efforts have a risk of failing to provide solutions that are environmentally, economically and socially beneficial due to the prevalence of narrow approaches to sustainability [10]. Within a remanufacturing environment, a lack of information on the condition of returned products and a shortage of advanced technologies for cleaner production have diminished the reach of CE principles [11]. Additionally, the uncertainty regarding costs in comparison with the return on investments and timeline for implementation has resulted in a reluctance from organisations to adopt the CE approaches [12]. However, the advent and adoption of digital technologies based on the principles of Industry 4.0 may help to overcome the barriers to the adoption of CE [12].

2. Problem Statement

According to IEC 60034 23 [13], the international standard for rotating electrical machines, replacing the bearings in a 110-kW electric motor doubles the life of the machine whilst retaining 99% of the original structure. In addition, the EU Directive on end of life vehicles [14] has set targets to promote the reuse, recycling and recovery of materials (the total mass percentage of materials reused and recovered relating to the vehicle's net weight must be equal to 95%, out of which a minimum of 85% must be from reuse recycling). However, the market for returned electrical machines is highly complex and unstructured, and remanufacturing organisations around the world are exploring new ways to enhance their productivity. Within electric motors, a wide variety of topologies and materials are utilised in design and manufacture. By way of example, electric motors variously consist of cast iron, electrical steels, plain carbon steels, aluminium, copper and, in the case of permanent magnet synchronous motors, some high-value, rare-earth-based permanent magnet alloys. As a result, there is a huge variability in the degree of wear and tear under different operating conditions, leading to a mainly manual process with increased costs and reduced efficiencies [15]. Evidence from different industrial sectors suggests that due to the variety and consequent complexity involved in decisions and operations related to the reuse, remanufacture and recycling of electric machines, manual operations feature prominently with very little automation currently involved. The predominance of manual operations and lack of automation not only contributes to low productivity but also brings the challenge of maintaining a high level of control and tolerances within the process in order to satisfy the requirements of key end-of-line tests. It is evident that manufacturing tolerances in the production process can have a significant influence on the operating behaviour of electrical machines [16].

Recently, there have been investigations into improving the control of remanufacturing processes by means of incorporating automation, the Internet of Things, and other forms of digitisation [17]. This study identified 29 research areas to optimise Industry 4.0 technologies for remanufacturing; it concluded that greater automation offered marked benefits in the remanufacturing processes to enabled the utilisation of Industry 4.0 concepts. The emergence and uptake of technologies based on the Industry 4.0 concepts present a means to overcome some of the barriers associated with the lack of information about the condition/quality of returned product to fully implement CE principles for electrical machines. Pairing the digital developments with the principles of the CE model has the potential to transform the industrial landscape and its relationship to raw materials and finite resources.

3. Common Circular Economy Strategies for Electric Motors and Impacts

A discussion of various types of electric motors from a sustainability point of view is presented in [18]. Common circular economy strategies for electric motors, as discussed in [19], are reuse, refurbish, remanufacture and recycle. Reuse, which is a product life extension strategy for the circular economy, is the process of reusing a component after cleaning and testing without further major processing. Remanufacturing is a circular strategy of product life extension that aims to keep the product or component at its highest utility and value [6]. It involves complete disassembly of a product and recovery at a component level. Refurbish is also a circular strategy of product life extension, and it shares few similarities with remanufacture. Refurbished products are returned to use conditions with a warranty shorter than a newly manufactured product, whereas remanufactured products are restored to useful life with a warranty and quality comparable to a newly manufactured product [20]. Remanufacturing of automotive components such as starter-motors, internal combustion engines, water pumps, etc., account for two-thirds of all remanufacturing activities in the world [21], and this trend is expected to increase with a step growth in the adoption of hybrid and electric vehicles. Recycle, which is an end-of-product-life strategy, involves processes such as shredding, melting, etc., to process waste streams of post-consumer products with an aim to capture (nearly) pure materials [6].

A methodology for selecting the best end-of-life scenario (reuse, remanufacture or recycle), from an environmental point of view, for small electric household equipment that has developed a fault before the end of its intended life span has been presented in [22]. This study suggests that in the case of small motors, if the failure has occurred at, or towards, the end of its expected life span, replacement is a better option as compared to repair and reuse. This is because, in this case, the environmental impact of the repair activities is not balanced by the benefits of a short extension of the useful life of the product. However, a similar study for higher power electric motors has not been found in literature.

As predicted by the Advanced Propulsion Centre, the market opportunity for electrical machines and power electronics in the UK is expected to be around GBP 12billion by the end of 2025 [4]. However, a key requirement for achieving these growth targets would be the UK's access to rare earth materials that contribute to 40–60% of the materials' cost for electric machines [4], in view of a few resource rich nations having a global monopoly in supplying the rare earth materials for magnets. This highlights the pressing need for a sound research and development capability for CE for materials used in electric motor manufacturing, particularly for rare earth materials. According to a recent study by the Birmingham Centre for Strategic Elements and Critical Materials [23], the UK scraps more End-of-Life vehicles than any other country, and nearly 80% of the metal products classified as waste in the UK are exported from the country. These figures again highlight the need to develop CE processes for mitigating the criticality of many raw materials. Recently, Bonfante et al. [24] have presented a review of the sustainability aspects (including economic aspects, social impacts and environmental impacts) for rare earth materials used in electric motors. The environmental footprints during the mining process of rare earth materials have been discussed in [25] and on energy consumption during the production process [18].

Although the interest in the area of circular economy for electric motors is growing, the research is still in its infancy. More research on application demonstrations would prove its usefulness and encourage further adoption of Industry 4.0 in existing industrial infrastructures. This paper makes its contribution to knowledge by carrying out a thorough literature review in order to create a holistic picture of the research progress made so far within this field. Products involving electronic circuits and software were beyond the scope of this research and therefore this aspect is not considered in detail. Further information in this area can be obtained from [26]. To capture the current landscape within the UK for repair, remanufacture and recycling of electrical machines, a structured survey of UK-based companies was conducted. The survey revealed that nearly half of the companies do not undertake any repair strategies for electrical machine components; however, there was an aspiration from the respondents to migrate their companies towards more sustainable activities. Two of the companies who responded are already involved in repair strategies, but many of these are focused on repairing or recycling their own production parts. The literature review and industrial survey led to identification of research trends, gaps and recommendations for future research. In this regard, the remainder of the paper is structured as follows: section four presents an overview of the main components of an electric motor and their remanufacturing processes. Section five presents the research methodology, and section six discusses the results obtained from literature review. Section seven compares the findings from the literature to the results from industrial survey. Section eight includes the state of some Industry 4.0 technologies in circular economy considerations for electrical machines. Lastly, sections nine and ten identify research gaps and draws conclusions with some recommendations for future work, respectively.

4. Overview of the Main Components of an Electric Motor and Their Remanufacturing Processes

In common with many other energy conversion and propulsion components, the main steps in the repair/remanufacturing operations for an electric motor are: collection of the returned products, primary inspection and sorting, disassembly, inspection and grading, fault diagnosis and prognosis, reconditioning and repair, testing and final assembly and the controlled disposal of materials (if required). A simplified process of the remanufacturing of parts of an electric motor has also been discussed by Casper and Sundin [27]. Low-voltage induction motors are the mainstay of numerous industrious operations, and despite being rather mundane machines with modest performance, their sheer number in service ensure that they are of enormous importance in many industry sectors. The main components of a 3-kW brake motor and key remanufacturing steps are described in this section.

- Collection (returned products): The reuse/repair/remanufacturing process begins with the collection of returned products; a typical attrition rate for electrical products is around 3% [28].
- Primary inspection: A primary inspection is conducted based on the product's physical condition; this includes conducting initial tests (for example resistance measurement tests, insulation to casing, etc.) to determine whether the product has an electrical fault, a mechanical fault or both.
- Disassembly: The disassembly sequence of a returned product is not necessarily an exact reversal of its assembly sequence due to the variation in degree of degradation or damage to components during use, missing components and product upgrade during past maintenance or repair tasks. Some components of an electric motor, e.g., the rotor, can often be reused without the need for full disassembly, whereas other components, for example, bearings or windings, require proper reconditioning and disassembly so that they can be used in a remanufactured product [29]. The images in Figure 1 show the key components and their disassembly steps for a 3-kW brake aluminium motor (IE3 and IE2 efficiency) that was returned after breakdown: (a) The motor has an outer casing made of aluminium. The screws and fixings were unscrewed via a predominantly manual process. (b) The electrical connections and the case for motor body are unscrewed. Initial tests are conducted for determining the nature of the fault. (c) The integral cooling impeller was detached manually. It is worth noting that in many higher power motors, the impellers are often manufactured of steel and/or aluminium. (d) The fixings and screws for the drive key and the in-built brake were unfastened using an extensive toolkit. A detailed description of destructive or non-destructive tools for disassembly operations (such as handling and separation tools) has been included in the literature [30]. (e) At this stage, the shaft has to be minutely inspected for any signs of damage. This is a prerequisite step before any couplings could be extricated from the shaft, as any damage to the shaft during

the removal of couplings could make it difficult to reuse the components because of the often exacting requirement on the shaft's surface finish. (f) The aluminium end cover is unscrewed, and the end seals are inspected for any signs of damage. Any mechanical problems related to bearings are also inspected, as a faulty bearing would cause a wear on the inside of the end cover and/or the shaft. According to a report by ABB [31], 51% of the motors fail due to faults in bearings and hence the most common repair in electric motor is the exchange of bearings [19]. (g) This step shows the separation of shaft from the stator. On a permanent magnet motor, the operation of removing the rotor from the stator while keeping it concentric with the stator bore often requires complex tooling due to the presence of very significant and destabilising magnetic forces between the shaft and the stator and the small clearances (order of 1mm or below in many machines). (h) When the rotor is detached from the shaft, the windings can be visually inspected for damage such as burn marks, etc. Any damage on the bore of stator core caused by touch-down of the rotor can also be detected. (i) The core is tested using various core testing equipment in line with standards on core condition assessment [32]: for example, core loss testers can indicate whether the stator core losses have been affected during the winding removal process. Any damage to the stator/rotor core (e.g., air gap surfaces of cores are damaged or the teeth on the end laminations are splayed) will increase the losses and affect the efficiency of the motor [32]. (j) The windings are tested electrically using a number of standard test method to detect any problems in the conductor, terminations or, more likely, the electrical insulation. If a winding fault is detected, then a partial or full rewinding is usually undertaken rather than effecting a localised repair of the damaged insulation/conductor [33]. In order to remove the windings, the varnish and the insulation needs to be broken down in a controlled temperature burnout oven. This process degrades the interlaminar insulation and can lead to a drop in motor efficiency, which is often cumulative and limits the number of occasions on which a core can be repaired/remanufactured. According to [34], 16% of the motors fail due to faults in stator windings and hence the second most common repair after bearing replacement is a rewind of the stator windings [19].

- Inspection, fault diagnosis and final tests: An inspection of the components is conducted to investigate the current condition of a component and detect any faults. Generally, the components can be categorised as follows [34]: (a) can be directly reused, (b) can be reused after repair or reconditioning and (c) cannot be repaired or reconditioned. Components that can be reused after repair or reconditioning are sent for cleaning, fault diagnosis and prognosis, whereas the components that cannot be repaired or remanufactured are sent for disposal. The strategy for reconditioning is dependent on the current state of the product or component and the failure mode. A damaged or worn part can either be repaired or replaced, depending on the severity of the damage [35]. The stator and rotor are assembled before the final end-of-line tests [36], after which the product is finally assembled.

Figure 1. Overview of the key components and disassembly steps for a brake motor. The details provided in the figure were obtained through observation of three disassembly processes at an electric motor repair/remanufacturing facility.

5. Methodology for Literature Review

A literature review was conducted to assess the full breadth of knowledge on circular economy for electric motors. The methodology used for the review and main quantitative findings are presented in Figure 2. This method involved a literature search from Scopus, ScienceDirect and Google Scholar databases, followed by quantitative and qualitative analyses of the identified papers. The search was conducted by adopting a series of combinations of two keywords "recycle"/"remanufacture*"/"reuse" AND "electrical machine"/"electric motor"/ in the titles, abstracts and keywords of papers for the scientific documents published in English language between 2011 and 2021. The identification and collation of the critical studies was conducted using the steps explained in Figure 2. Finally, 69 publications were considered for meta-analysis, unpublished data was not included.

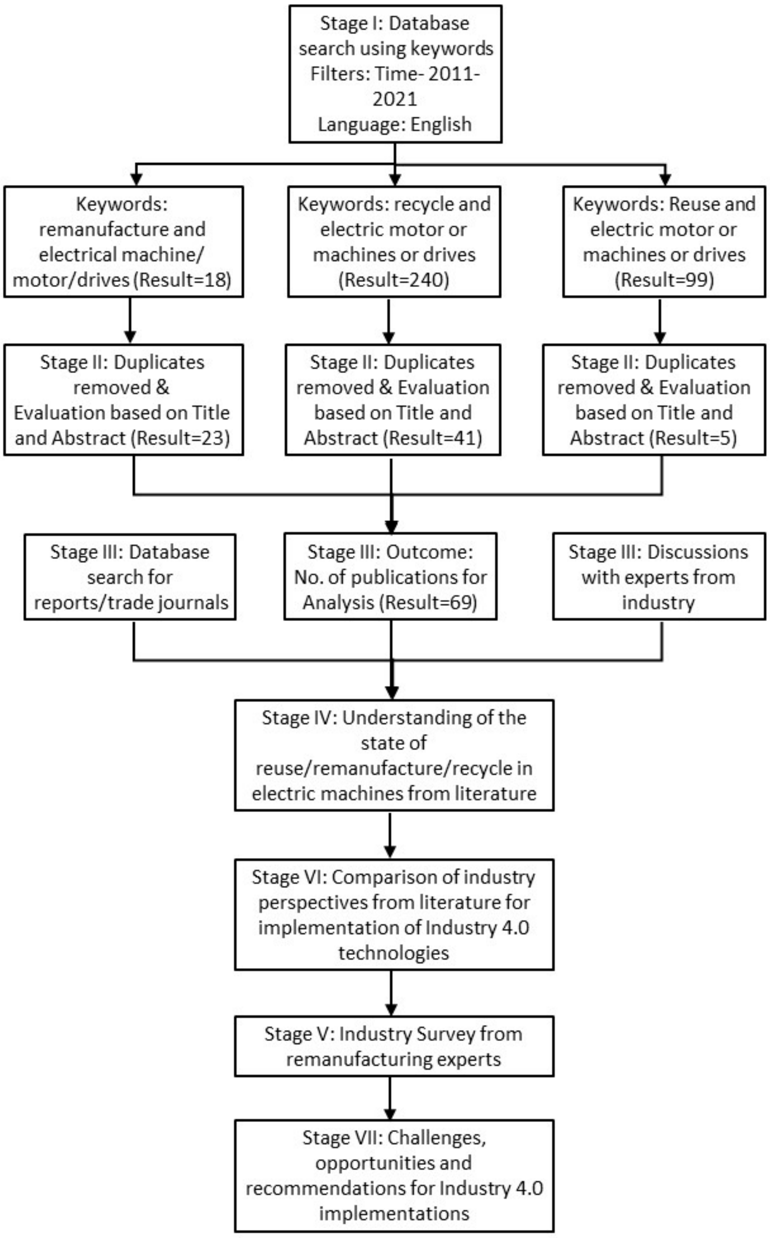


Figure 2. The methodology used for the review and main quantitative findings.

6. Results

6.1. Reuse, Remanufacture and Recycle within the Context of Electric Motors

The output of the literature search process in terms of number of articles published focussing on reuse/remanufacture/recycling of electric motors per year is presented in Figure 3. The growing number of total articles reveals the increased attention devoted to these topics, especially from 2017 onwards, with about 74% of the documents published within the decade under consideration being published between 2017 and 2021. Recycling, which is an end-of-product-life strategy, is the focus of the highest number of papers with remanufacture, which is a circular strategy of product life extension, being the second most reported area of research. Reuse, which is also a circular strategy of product life extension, has to date attracted modest interest, at least as measured by published outputs.

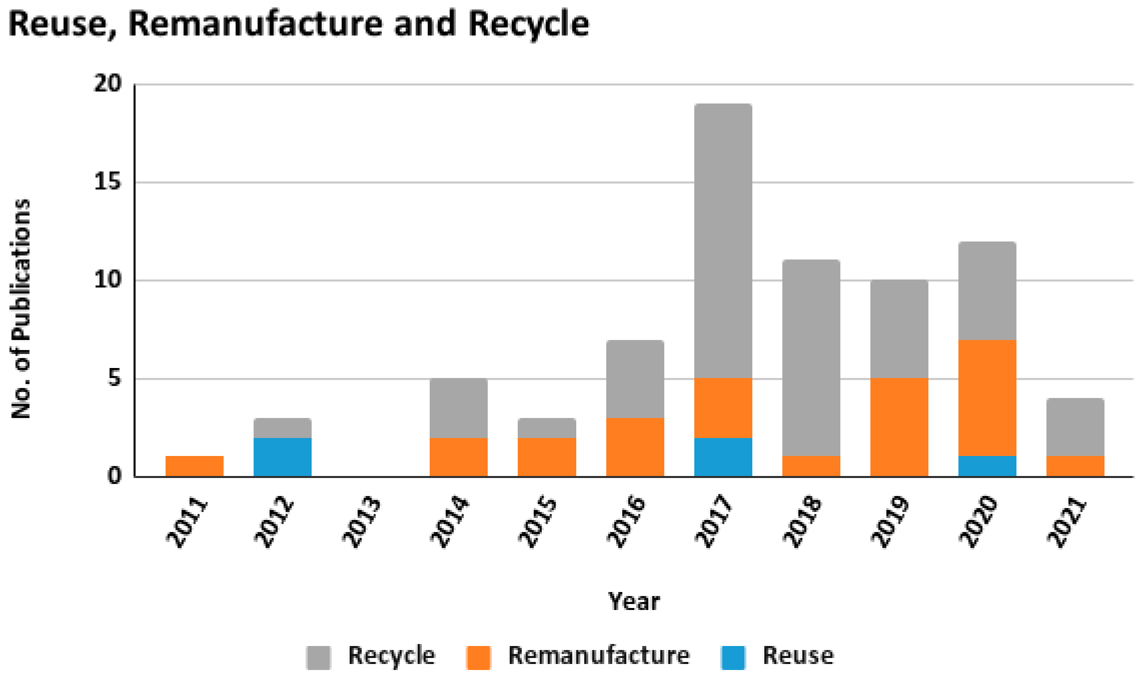
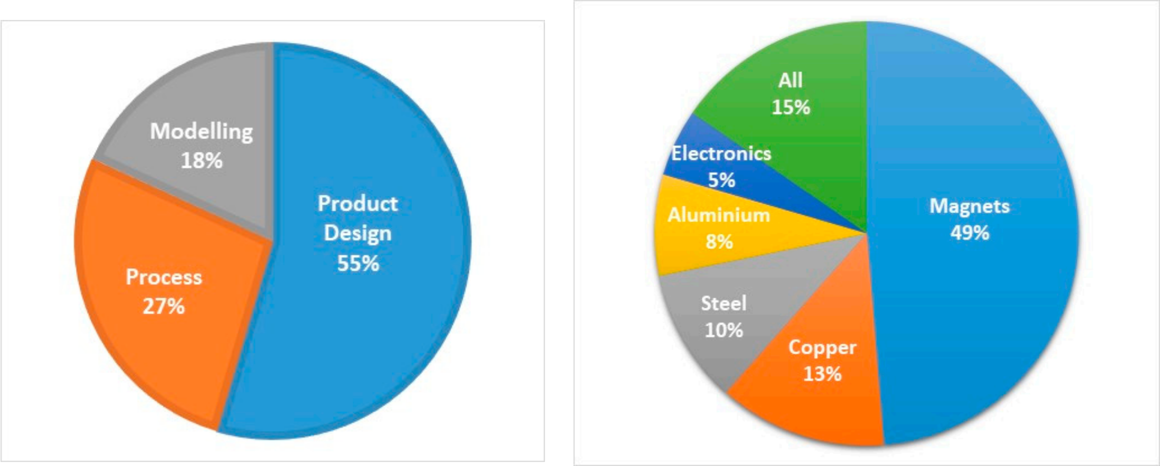


Figure 3. The trend in published literature from 2011 to 2021 (partial) in the reuse, remanufacture and recycle of electric motors.

Reuse is a better strategy in terms of the waste hierarchy, but it may not be a feasible option due to a lack of information concerning the condition and availability of returned products. Hence, reuse is a relatively less researched area for electric motors (Figure 3). An example of the challenges in the reuse of stators is that an insulation test conducted on the stator is generally a global test that cannot locate the defect point of the insulation, which makes it difficult to reuse or repair it. If the exact insulation defect point can be detected by conducting tests, then the stator can be reused by minor repair only, thus improving the productivity of the reuse process [37]. Similarly, if the magnets in a motor are not damaged during the dismantling process, then it may be possible to reuse them after demagnetisation [19].

Remanufacture: The circular strategy of remanufacture shares many similarities with refurbishment. Li et al. [38] has summarised the differences between motor remanufacture and repair: the purpose of motor repair is to restore function that usually happens with a reduced efficiency, whereas the purpose of remanufacturing is to transform the returned product into a high efficiency motor with an aim of restoring the as-designed efficiency. In terms of service life, the process of repair involves replacing faulty parts and therefore the motor tends to have a shorter service life. The process of electric motor remanufacture involves replacing the elements which are known to exhibit ageing and/or primary sources of failure, e.g., stator windings, insulation and bearings, so that the service life is consistent with the new motor. Currently, one of the following solutions are adopted in the process of remanufacturing for high efficiency electric motors [33]: the rotor core is retained, the shaft, bearings, insulation, impellers and windshields are replaced, and windings are replaced/rewound or the stator core is retained, the rotor core, shaft, bearings, insulation, impellers and windshields are replaced, and the winding is rewound.

As depicted in Figure 4a, more than half of the remanufacturing papers focussed on a resource-efficient product design of motor or its components, for example, replacing the squirrel-cage rotors of induction motors with efficiently designed permanent magnet rotors [33], replacing the cast-aluminium rotor with a cast-copper rotor [15] or the elimination of rare earth magnets from the design [39]. Around a quarter of the papers focussed on energy- or resource-efficient remanufacturing processes [40], e.g., disassembly of motors [30], coil rewinding, etc. Some studies focussed on simulation and experiments to verify the feasibility of remanufacturing the asynchronous motor [9].



(**a**) (**b**)

Figure 4. (**a**) Distribution of research focus of papers in remanufacturing; (**b**) Distribution of research focus of papers in the area of recycling.

Recycling: The EU Directive on end-of-life vehicles [14] aims to reuse and recover 95% of the total mass percentage of materials in a vehicle. However, these recycling targets are based on vehicle mass rather than other considerations such as material cost, scarcity, embedded energy, etc. To meet these targets, effort is more focused on those metals that constitute a significant proportion of mass (for example, steel, aluminium and copper), creating a risk that scarce metals are not being functionally recycled [41] (i.e., not reverted to material streams where their specific properties are utilised). They may culminate in a recycled residual waste or not be recycled at all. Andersson et al. [42] analysed 25 scarce metals and investigated the extent to which they were recycled. The study revealed that out of 25 scarce metals, only platinum was functionally recycled; approximately 60% of other metals (for example, chromium) inadvertently ended in steel-making process [43].

The rare earth magnets, especially the NdFeB type, are essential components in many high-performance electric motors and wind turbine generators. As shown in Figure 4b, around a half of the published articles in the area of recycling of electric motors focussed on recycling of magnets. The other focus areas were copper, aluminium and steel. Commonly, magnets are recycled by breaking down the rare earth materials to a fine power using various technologies (such as hydrogen embrittlement) and the powder is reprocessed into magnet material again, with a remanence loss of up to 3% [19]. A systematic review of past work on the high-temperature (pyrometallurgical) recovery is presented in [44] and on hydrometallurgical recovery in [45]. A detailed review of various aspects of sustainability in REM supply chain is presented in [24]. Prosperi et al. compared the performance of motors fitted with recycled magnets and conventionally manufactured sintered magnets and reported that recycled magnets performance was competitive with virgin magnets [46]. In spite of this, the current functional recycling rates of some metals are very low because, in some cases, recycling processes are more costly and time consuming as compared to primary raw material extraction [47].

6.2. *Distribution of the Published Work*

Figure 5 displays the geographical distribution of published articles. This distribution is concentrated mainly to Germany, China, the UK and the USA, with these four countries contributing to approximately 50% of the total number of published articles. Germany occupies the first position with 14 publications, followed by China with 12. The countries with fewer than two publications have not been included in the graph. Figure 6 displays the distribution of published articles in journals and conferences. *Environmental Science and Technology* was the most popular journal, and the Procedia CIRP conference was the most popular conference for publication in this area. The journals and conferences with fewer than two publications have not been included in the graphs.

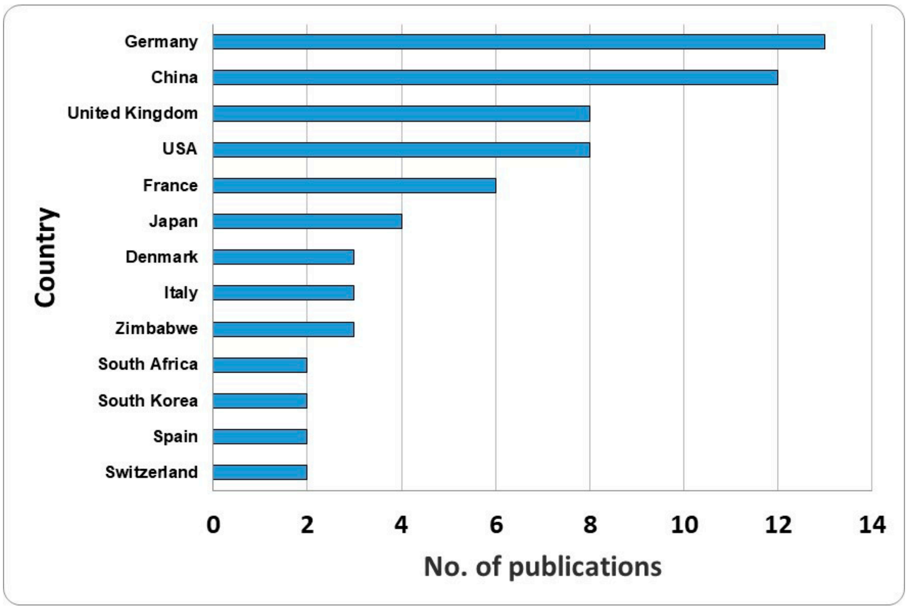
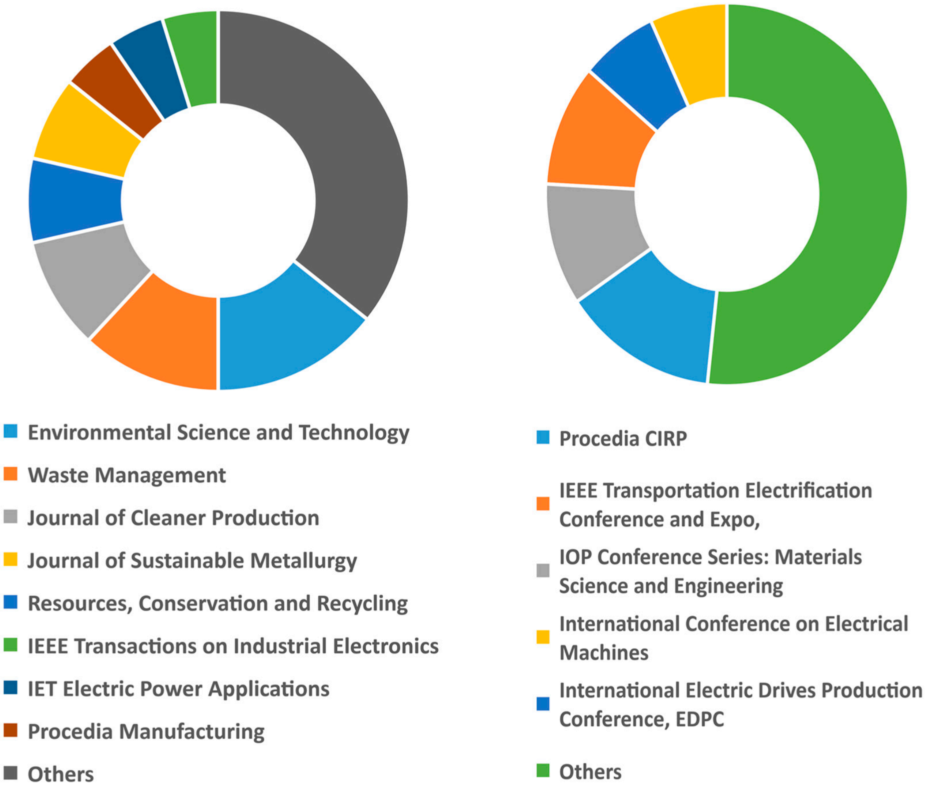


Figure 5. Geographical distribution of published articles in journals and conferences.



(**a**) (**b**)

Figure 6. Distribution of published articles in journals (**a**) and conferences (**b**).

7. Industrial Perspectives and Motivation

In order to understand the current landscape within the UK for reuse, repair, remanufacture, and recycling of electrical machines, an industry survey was conducted. The main aim of the survey was to understand the gaps and challenges in this area in the UK and the support required for UK-based companies to expand their capabilities to accommodate higher volumes of electrical machines. The methodology adopted for this empirical study is explained as follows:

a. A questionnaire was prepared, by researchers from the Universities of Strathclyde and Sheffield, based on the understanding of the state-of-the-art in the circular economy of electric motors from the literature. A copy of the questionnaire has been attached as the supplementary file. The survey targeted companies in the CE of electric motors/components from low power (less than 100 kW) to high power (more than 1 MW) from the following sectors: aerospace, automotive, rail, marine and wind. The full breadth of companies ranging from SMEs dealing with small volumes to large manufacturers handling large volumes were included in the survey. All types of motors including permanent magnet, induction and reluctance motors were included in the survey.
b. The questionnaire was validated and approved, and it was presented to industrial organisations involved in the manufacturing and overhaul of electrical machines. The industrial organisations were sourced from the network of the authors' and The EPSRC Future Electrical Machine Manufacturing Hub.
c. The responses and empirical data were collected in Tables 1–3 for five recently surveyed companies that deal with CE processes for electric motors. These companies, which are designated A–E in the subsequent Tables span electrical motors for the aerospace, automotive, industrial and marine sectors with company sizes ranging from 50 headcount to >1000 headcount. The respondents had 10+ years of experience and were involved in the manufacture/remanufacture of medium to high value motors in low to high volumes.
d. The industrial perspective was compared with findings from literature and that led to identification of challenges and opportunities for the CE considerations for electric motors.
e. The industrial perspective on circular strategies for electrical machine components is presented in Table 2. A few key elements of information sought from the questionnaire were:
    - Discussion on the type of motors processed in their business;
    - What components of the motor are considered for reuse/remanufacture or recycling?;
    - Discussion on the degree of involvement of manual operations and automation in CE activities related to electrical machines;
    - Do they currently employ digital solutions in their business, or would they be interested in employing them?;
    - In the future, could it aid in the reuse of electrical machine components?

From the responses, it was clear that there is already a diverse range of CE activity ongoing within the UK and the EU and in a range of sectors and machine sizes. One of the respondents is involved with no fewer than five different sectors and deals with a range of electrical machines from low power (less than 100 kW) to high power (more than 1 MW) machines. The aerospace and marine sectors both had representation from multiple companies across the full range of machine sizes. The results from Table 1 show that there are extensive opportunities for the development of electrical machine activities within the UK, with strong representation across five key applications within the transport and energy sectors.

Table 1. Industry perspective on the applicable scenarios for manufacturing electrical machines/components provided by five companies (A, B, C, D and E).

	Manufacturing Activity and Volume	**Up to 100 kW**	**100–500 kW**	**500 kW–1 MW**	**Larger Than 1 MW**
1	Aerospace	A, B	A, B	A, B	A, B
2	Automotive	B, D, E	B	B	B
3	Wind	B	B	B	B
4	Marine	A, B	A, B	A, B	A, B
5	Rail	B	B	B	B
6	Other	E		C	C
	Manufacturing Activity Volume	**Less Than 10 Machines/Month**	**11–50 Machines/Month**	**51–100 Machines/Month**	**More Than 100 Machines/Month**
7	Aerospace	B			A
8	Automotive	D		E	B
9	Wind		B		
10	Marine		A		B
11	Rail			B	
12	Other			E	

Table 2. Industry perspective on circular strategies for electrical machine components provided by five companies (A, B, C, D and E).

	Component	**Recycle**	**Remanufacture/Refurbish**	**Reuse/Redistribute**	**Maintain/Prolong**	**Scrap**
1	Coils	C				A, D, E
2	Magnets	E				A, D
3	Laminations			C		A, D, E
4	Housings/casings			C, E		A, D
5	Power electronics					A, D, E
6	Auxiliaries			E		A, D
7	Other	B	B	B	B	A, D

Table 3. Industry perspective on current and future digital solutions provided by the five companies (A, B, C, D and E).

	Technology	**Yes, Currently Employed**	**Yes, in the Process of Being Implemented**	**No, but Interested in Employing in the Future**	**No, Not Interested in Employing in the Future**
1	Sensors	B, C, E	A	D	
2	Data from sensors	B, C, E	A	D	
3	Machine learning		A, B, E	D	
4	Computer vision		A	B, D	
5	Simulation and Digital twin	B	A	D	
6	Robotics	B	A	D	
7	Additive Manufacturing		A	B, D	

The volume of machines handled by the respondents across different sectors is varied, with an even spread across all sectors and monthly volumes. As demonstrated by the responses in Table 2, half of the companies do not undertake any repair strategies for electrical machine components; however, there was an aspiration from the respondents to migrate their companies towards more sustainable activities. Three of the companies who responded to the survey are already involved in repair strategies, but many of these are focused on repairing or recycling their own production parts. Closed loop cycles are an excellent opportunity to track materials and components throughout the lifecycle and maintain quality standards of remanufactured components. A closed loop cycle will not be feasible in all situations, and the challenge will arise from balancing internally focused remanufacture, with a wider circular economy infrastructure.

As demonstrated by Table 3, all the respondents were currently employing digital solutions in their companies or were interested in employing them in the future. The willingness from the industry to adopt digital solutions to aid in their activities suggests an opportunity for collaboration between electrical machines/drives research community and digital manufacturing researchers.

8. Industry 4.0 as an Enabler for the Circular Economy of Electrical Motors

Industry 4.0 drives the manufacturing and remanufacturing industry into a new era of autonomous and intelligent information exchange, machine control and interoperable production systems. One of the key goals of Industry 4.0 is connectivity and the integration of elements from the production environment [48]. This will allow companies to build a data footprint through sensors and monitoring of machines and equipment. However, the potential of Industry 4.0 technologies in repurposing of end-of-life products is yet to be realised [49]. In this section, some relevant Industry 4.0 technologies have been discussed in the context of remanufacturing operations of electric motors:

8.1. Sensors and Machine Vision for Inspection

According to a recent report by the Association of Electrical and Mechanical Trades [50], the smart sensors for motors can open up new opportunities for motor repair business. These sensors can be attached to the motor frame to monitor the motor's performance and detect problems such as bearing faults, air gap eccentricity and overloading, revealing issues that account for 70 percent of motor failures. Intelligent sensing for the robotic remanufacturing of jet engine compressor blades was developed by French et al. [51]. This incorporated machine vision systems for characterization, inspection and fault detection during remanufacturing of a turbine blade. The real-time sensor data collected during the process were combined with information regarding each individual blade, embedding data analytics and the Internet of Things into the remanufacturing process. Research reported in [52] investigated creation of an automation cell for an aircraft fan-blade repair with the integration of a 6-DoF industrial robot with an end-effector grinder and a computer vision system. Another study reported the use of vision-guided robotic technology for ultrasonic inspection of components in returned products [53].

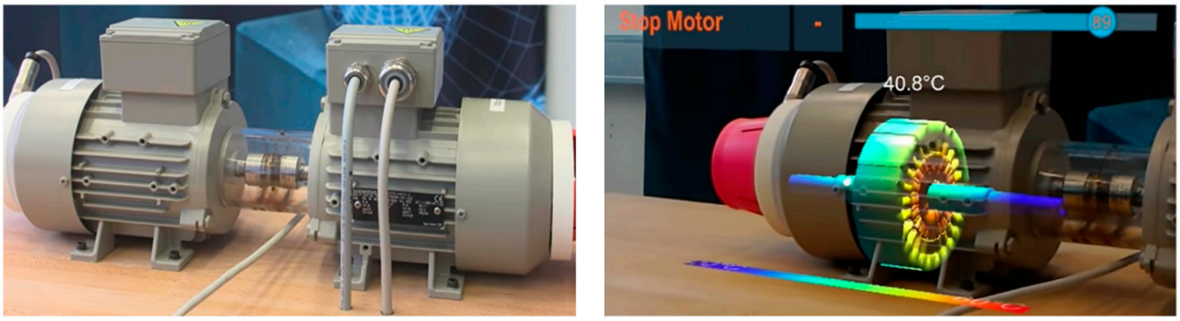
8.2. Robotic Applications for Disassembly

The disassembly process is one of the most important processes in the CE process and has been identified as a key link that connects product return with product recovery [54]. Currently, the disassembly of electric motors is almost universally a manual task that is difficult to automate due to the high number of variants and unknown conditions and specifications of the components in the returned products [55]. The main process steps carried out by a disassembly system are the handling and clamping of product and components, the separation of connections and checking the state of the product and its components [30]. Recent research at the University of Birmingham presented a novel technique for automating the unfastening of screws [56] that improved the rate of successful engagement between the robot-end effector and the screw heads. Recently, research from the Karlsruhe Institute of Technology from Germany reviewed the state-of-the-art in flexible disassembly systems and demonstrated the development of a robot-based flexible disassembly system for electric motors [30]. The disassembly system comprised of four subsystems: kinematic, tools, work-piece station and the associated safety system. A discussion on challenges in the robotic disassembly of electrical components has been provided in [57] where a robotic technique for disassembly for strategically important materials is also presented.

8.3. Modelling, Simulation and Digital Twin for the Decision Making Process

Digital modelling and simulation could support in decision making in operations related to the CE of electric of motors. Previous work has investigated simulation to inform decision making processes in remanufacturing taking into account the stochastic nature of returned electric motors [9,58,59]. A data-driven simulation approach to predict material flow behaviour at a waste electrical and electronic equipment remanufacturer [60] and symbiotic simulation for assisting in decision making has been reported [61]. Recently, the development of an economic assessment of robotic disassembly for end-of-life products has also been presented [62].

A digital twin can also be adapted in a remanufacturing process to assess the damages, for example, stator core lamination damage, impact of lamination burnout, etc. This can aid in determining whether the returned electric motor should be reused, remanufactured, recycled or discarded as waste. A digital twin is a virtual replica of its physical asset built mainly of structural and behavioural models mainly for basic control, monitoring and evaluation of its performance [63]. By enabling integration of both physical and virtual spaces, a digital twin of a system can provide the integrated platform necessary to harness the potential of generated data. This would see more data-based corrective actions taken in real-time to optimise production lines and increase productivity. Developed by Siemens, a virtual X-ray of electric motors is a digital twin that enables monitoring of the real-time performance of an electric motor by utilising thermal simulations to obtain information about temperature distribution inside a motor [64]. Figure 7 shows a table-sized demonstrator of an electric motor and its digital twin. Researchers at Siemens Corporate Technology (CT) developed this digital twin with virtual sensors to measure and monitor the temperature of the motor components during operation. Using an augmented-reality headset to view the demonstrator of the motor enabled the user to view the simulation of the motor and its interior with a real demonstrator superimposed over it. Colour scales indicated the temperature levels. This type of digital twin can be adapted to investigate the extent of damage in a motor and aid in decisions in choosing an appropriate CE strategy.



(**a**) (**b**)

Figure 7. A stepper motor (**a**) and its digital twin developed by Siemens Ltd. (**b**) (Source: [64]).

9. Challenges and Proposed Solutions through Industry 4.0 Technologies

A comprehensive review of challenges and opportunities of the CE within manufacturing domain has been presented in the literature. Kumar et al. have discussed the barriers and opportunities of CE from an economic, legal and environmental perspective [65], Diaz Lopez et al. [66] explored relevant technical barriers, and financial and organisational challenges have been discussed by Sousa-Zomer et al. [67]. This section presents the challenges in CE considerations for electric motors, and some solutions through Industry 4.0 technologies have been proposed.

9.1. *Lack of Data about the Condition of the Returned Product*

A key barrier to the reuse and remanufacture of electric motors is the lack of information about the condition of the returned product, e.g., whether the returned product has a mechanical fault (damaged shaft) or an electrical fault (damaged insulation). Industry 4.0 technologies have the potential to solve this challenge by tracking the products in use by utilising embedded sensors. For example, Fibre Bragg Grating sensors embedded with stator windings could highlight winding or insulation damage by indicating an increase in temperature. Data obtained from embedded sensing system can extend the lifetime of the product/components for reuse or remanufacture or to inform end-of-life strategies such as disassembly and recycling. A 'product passport' could display information about materials contained in the product to facilitate reverse logistics and CE strategies. For example, by obtaining and analysing data/information about each used magnet, the required magnetic tolerances can be checked and reject rates can be reduced.

9.2. Disassembly Process Is Manual, Complex and Expensive

Due to huge variability in the degree of wear and tear in the returned electric motors, the disassembly and inspection is mainly a manual process with increased costs and reduced efficiencies. The predominance of manual operations and lack of automation contributes to labour costs and low productivity. Research by Soh et al. have proposed a methodology and guidelines for a systematic design for the disassembly for the remanufacturing of electric motors [68]. However, as discussed in Section 8, this research is still at a low technology readiness level and needs to be further developed.

9.3. Recycling of Some Components of an Electric Motor Has Traditionally Been Difficult

Some components of an electric motor, for example, the copper wire, comprises of several materials such as paint or insulation from the coating, connectors, lead from solder terminals, tapes, etc. All of the extraneous material needs to be removed from the copper before the recycling process is conducted, as a failure to do so can have a negative impact on the properties of the recycled copper. The complex and time-consuming process of removing unwanted material before recycling has been a challenge in efficient recycling of electric motor components.

9.4. Lack of a Methodology for Deciding the Best End-of-Life Scenario for Electric Motors

A methodology for selecting the best end-of-life scenario for small household electric equipment has been discussed in the literature. However, the literature review by the authors did not reveal a similar study for higher power electric motors.

9.5. Cost vs. Return on Investment

Some companies have reported using an efficiency calculator to decide on whether to repair or replace a motor. For example, if an electric motor can be repaired for less than 57 percent of the price of a new motor, then it was repaired; in case the costs associated with repair exceeded 57 percent then a new motor was ordered [69]. In several cases, unclear economic benefits with respect to investment costs has been seen as a major challenge in decisions regarding an appropriate CE activity for electric motor components. A detailed analysis on investment costs with respect to the financial and environmental benefits/returns for electric motor components could be useful.

10. Conclusions

The supply chain for raw materials, particularly rare earth metals, provides a key motivation for the application of circular economy for electric motors. The UK lacks indigenous production of rare earth, technology-critical metals and is dependent on resource-rich countries for an uninterrupted supply. According to recent literature reports, the worldwide recycling rate for high value, rare earth materials used in electric motors is less than 3%. Additionally, 80% of the metal waste in the UK is currently sent outside the country. These alarming figures highlight the need for the UK and the policy makers to invest in developing CE strategies and processes for mitigating the criticality of key raw materials and hence play an important role in building a well-positioned supply chain for the future. In addition to this, the current framework for incentives and guidelines for CE for electric motors is also not clear, because, in some cases, the economic and environmental impact of the CE activities is not balanced by the benefits of an extension of the useful life of the product or component. In addition, decision makers in industry should evaluate the cost-benefit analysis for digital solutions to aid in CE for electric motors. More investment on application demonstrations would prove its usefulness and encourage further adoption of Industry 4.0 in existing industrial infrastructures.

This paper makes its contribution by presenting a holistic view on the circular economy research for electric motors and the role of Industry 4.0 technologies by presenting the state-of-the-art available in 69 articles from the literature and comparing it with the industrial perspective. An overview of the main components of an electric motor, their remanufacturing processes and the associated challenges have been discussed. The predominance of manual operations and lack of automation contributes to increased labour costs and low productivity in operations related to CE for electric motors. The literature review also highlighted the requirement for a methodology for selecting the best end-of-life scenario for industrial electric motors. As a key contribution, challenges in circular economy considerations for electric motors have been discussed and some key technologies based on principles of Industry 4.0 were proposed as enablers for circular economy of electric motors; however, this research is still at a low technology readiness level and needs to be further developed. Future work could involve a more in-depth analysis of the research areas at the interface between Industry 4.0 and processes related to CE for electric motors. To capture the current landscape within the UK for the repair, remanufacture and recycling of electrical machines, a structured survey of UK-based companies was conducted. The survey revealed that nearly half of such companies do not undertake any repair strategies for electrical machine components. The remaining companies focused on repairing or recycling their own produced parts. The electric motor industry has shown a willingness to adopt digital solutions to aid in their activities, suggesting an opportunity for collaboration between electrical machines/drives research community and digital manufacturing researchers. One of the limitations of this study was that a comprehensive industry survey could not be conducted due to COVID-19-related challenges faced by the industry. Future work could involve capturing the landscape beyond the UK for the reuse, repair, remanufacture and recycling of electrical machines. With an estimated figure of 2 million electric motors reaching their end of life in the UK annually, this paper provides a timely review of the state-of-the-art for achieving a circular economy for electric motors.

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